Regional coseismic deformation from the June 28, 1992, Landers, California, earthquake: Results from the Mojave GPS network

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ABSTRACT

The 1992 Landers, California, earthquake sequence and its aftershocks delineate an active part of the Eastern California shear zone. The surface rupture lies within the Mojave Desert, providing a unique opportunity to characterize far-field deformation with a regional Global Positioning System (GPS) network that was installed and occupied in May 1991, with uncertainties of less than 1 cm on interstation baseline vectors. Changes in absolute displacement vectors on the decimetre and centimetre level were determined for individual sites, providing mom samples of the sparsely sampled Landers displacement field. Measured displacements result from secular strain across the Mojave Desert, coseismic elastic recovery, and postseismic deformation during the six weeks between the earthquake and the GPS experiment. Secular strain and postseismic displacement are relatively small, Thus, first order modeling of these fields allows calculation and subtraction of their signals, leaving a coseismic residual field. The GPS-determined far field coseismic displacements differ significantly from elastic half-space models, offering new insight on the role of regional scale heterogeneity in crustal structure.

INTRODUCTION

The Landers earthquake in the Mojave Desert was the largest earthquake to strike California in 40 years. A fortuitous combination of location, magnitude, seismic instrumentation, and advances in space geodesy afford opportunities to characterize both the seismic source of a large earthquake (e.g., Kanamori et al., 1992) as well as the associated regional crustal deformation with great precision over an area that is significant] y larger than those studied by conventional geodetic techniques (this study; Blewitt et al., 1993; Bock et al., 1993). In 1991 we installed and occupied a regional GPS (Global Positioning System) geodetic network that extends as far north as Big Pine, California, spanning much of the Walker Lane; it includes the area of the Landers earthquake (Miller et al., 1992). After the earthquake, six sites in the southern part of this network (Fig. 1) were reoccupied with GPS to measure regional crustal deformation related to the rupture.

At 458 a.m. on June 28, 1992, a M_w = 7.3 earthquake awoke southern California, and was located -200 km east of Los Angeles in a sparsely populated region of the Mojave Desert. The Landers seismic events caused 70 km long zone of surface rupture that included segments of five faults (Sieh et al., 1993). The maximum surface offset was over 6 m; most displacements were between 2 and 3.5 m (Sieh et al., 1993). The largest aftershock (M_w = 6.2) occurred 30 km to the west, near Big Bear in the San Bernardino Mountains.

present-day relative plate motion between the Pacific and North American plates occurs at a rate of 49 mm/yr in southern California (DeMets et al., 1990). Only 35 mm/yr occurs on the San Andreas fault or, farther south, on the combined San Andreas and San Jacinto faults (Sieh and Jahns, 1984; Weldon and Sieh, 1985); the San Andreas fault is commonly regarded as the major plate boundary fault at this latitude. The remaining 14 mm/yr occurs on subsidiary faults, including the complex Eastern California shear zone (Dokka and Travis, 1990), faults farther east, or on additional parallel faults west of the San Andreas (Weldon and Humphreys, 1986). Conventional geodesy establishes that -7 mm/yr of northwest-directed dextral slip occurs within the Mojave Desert (Savage et al., 1990; Sauber et al., 1986), accounting for approximate y 15% of the relative plate motion. This zone, called the Eastern California shear zone, is recognized on historical seismic (Wallace, 1984), geologic (Dokka and Travis, 1990), and geodetic (Savage et al., 1990) grounds; it extends northward into the Owens Valley and Death Valley regions. The Landers earthquake aftershocks extended into northern California, coinciding with the Eastern California shear zone.

A sub-centimetre precision regional GPS network that spans the Eastern California shear zone afforded unprecedented measurements of regional coseismic deformation from the Landers earthquake. An independent measure of coseismic deformation is available from five stations of the southern California Permanent GPS Geodetic Array (PGGA; Blewitt et al., 1993; Bock et al., 1993), which mostly lie at greater distances from the surface rupture. Our regional network provides a denser spatial coverage than does the PGGA, although data collection is intermittent rather than continuous.

MOJAVE GPS NETWORK

The Mojave - Walker Lane GPS network was designed to measure slip along northwest-striking dextral faults and related sinistral faults east of the San Andreas fault. Although the Eastern California shear zone accounts for approximate] y 7 mm/yr of plate-boundary motion (Sauber et al., 1986), Very Long Baseline Interferometry (VLBI) geodesy indicates 1 1±1mm/yr of motion between the Sierra Nevada block and stable North America (Argus and Gordon, 1991). The rate and partitioning of this contemporary slip is not well understood. The Mojave GPS network was designed to measure plate margin slip partitioning.

Station displacements are based on two epochs of geodetic observations, 1.3 yr apart. Data were collected initially in May 1991, 1.15 yr before the Landers earthquake, and the second data set was collected in August 1992, 0.15 yr after the large earthquake. The May 1991 data were collected for the entire Mojave - Walker Lane network. Following the Landers earthquake, a subset of six sites within or near the Mojave Desert were reoccupied to measure changes in station positions.

For each experiment, station positions in the International Terrestrial Reference Frame 1991 (ITRF'91) were determined with GYPSYII software developed by JPL. Solutions for station position and covariance from each experiment were combined to yield the station displacements and uncertainties. The fiducial network for the May 1991 solution is sparse, thus, the reference frame was poorly constrained. Absolute station displacements were calculated by combining the relative station displacements with respect to Mojave with the absolute station displacement for Goldstone between May 1991 and August 1992. This approach assumes that coseismic and secular motion between Mojave and Goldstone is insignificant, and the distance between these stations was constrained to its ITRF'91 value. Although Goldstone and Mojave stations are in an area of tectonic instability, strain rates are very low (Ma et al., 1992), the time interval is short (1.3 yr), and the distance between the stations is small (10.4 km). Furthermore, consistent baseline length measurements before and after the earthquake, between Goldstone and the CIGNET station at Mojave indicate negligible coseismic deformation (Bock et al., 1993).

The distances between occupied GPS sites and the surface rupture of the Landers earthquake ranged from 20 to 100 km. Absolute displacements range from decimetre to centimetre level, with sites close to the rupture showing significantly greater motion (Fig. 2; Table 1). Formal errors for the 1992 occupation are comparable to those given for the PGGA sites; reference frame uncertainties from the 1991 occupation dominate for Mojave network sites. Total uncertainties are based on combined covariance of each day of GPS data. Uncertainties introduced by the 1991 reference frame are far greater in magnitude than anticipated unmodeled errors (Figure 2).

DISCUSSION

Displacements within the Mojave- Walker Lane GPS network include three components. (1) Secular strain accumulated across the Mojave Desert during the 13 months for May 1991 to June 1992. (2) Coseismic elastic deformation occurred during the June 28 earthquake sequence. .

(3) Postseismic deformation and negligible secular strain occurred during the 1.5 months between the earthquake and our GPS occupation. Secular strain and postseismic displacement are relatively small; first order modeling of these fields allows calculation and subtraction of these signals, leaving a coseismic residual field.

Secular Strain Accumulation in the Mojave Desert

Secular strain rates are relatively low across the Mojave Desert. Historic triangulation and trilateration data indicate that dextral slip occurs within the south-central Mojave Desert at a rate of 6.7 ±1.3 mm/yr along a plane oriented N41°W ±5° (Sauber et al., 1986; Savage et al., 1990). VLB1 results indicate about 10 mm/yr between Goldstone and stable North America (Ma et al., 1992), This rate is in broad agreement with longer term geologic constraints (Dokka, 1983; Dokka and Travis, 1990). Modem strain occurs in the western part of the Mojave Desert, along the Helendale, Calico, and intervening faults (Sauber et al., 1986). Thus, as much as ~8 mm of the relative displacement between station Monday and the stations Troy, Siberia, and Round Valley may be due to secular strain. Monday lies 25 km away from the San Andreas fault and was selected to minimize effects of San Andreas elastic strain accumulation on the historic time scales of geodetic work. All sites have appreciable motion beyond expected secular strain, here attributed to earthquake-related deformation.

Coseismic Deformation

Elastic half-space models can be used to predict recovery of elastic strain near a fault during catastrophic failure. parameters that determine the response of the lithosphere are earthquake specific and include depth and length of fault rupture, amount of slip, and crustal rigidity (Okada, 198S). Observations of geodetic strain and surface rupture constrain slip distribution; hypocenter location and aftershock distribution determine the rupture-plane dimensions. Near-fault geodetic measurements of coseismic deformation have been successful y explained by elastic-model predictions. As a result, such models are widely applied to evaluate seismic strain release and, to first order, reasonably predict the geodetically observed strain field. Conventionat geodesy measures near-fault deformation as changes in baseline length and changes in angles between groups of stations. Thus, no absolute displacements or rotations are determined.

GPS geodesy offers constraints different from those of conventional techniques. GPS is now capable of determining absolute point positioning and thus can measure displacements and rotations in a geocentric reference frame. Horizontal point positioning precision of GPS is potentiall y very great (a few millimetres plus one part in 10^9 of baseline length, Heflin et al., 1992). The Landers earthquake is one of the first such events where in-place geodetic networks have allowed mapping of regional deformation as much as 100 km away from the fault (see also Lundgren et al., 1993). Widespread GPS solutions provide a far-field test of the elastic behavior of the lithosphere.

Dashed vectors in Figure 2 show displacements predicted by an elastic half-space model based on Mansinha and Smylie (1971), constrained to fit surface displacement patterns and modified to fit three far-field GPS observations (Blewitt et al., 1993). Anomalously small displacements at Goldstone were fit by a shallow rupture depth along the northern fault segments, an interpretation that was later confirmed by revised aftershock locations. The displacement vectors at only three of the Mojave GPS sites, Round Valley, Black Butte, and Mojave, agree well with the model for both direction and magnitude. Observed vectors differ significantly in either direction or magnitude from model-predicted values at the three other sites. At Monday and Siberia, displacements are rotated -300 clockwise and counterclockwise, respectively, from the model directions. At Troy, the observed displacement is 150% of the predicted value, although direction is in agreement. The anomalous motion of Troy may result from underestimated postseismic relaxation, evaluated below. Alternatively, lateral crustal heterogeneity such as localized Neogene extension may have locally altered rigidity or thickness, causing a greater elastic response of the lithosphere.

For the Landers earthquake, tuning models to agree with small GPS data sets either in the near field or in the far field has been partially successful (Blewitt et al., 1993; Bock et al., 1993). Although elastic behavior of homogeneous crust explains near-fault deformation (Lisowski et al., 1992), other factors such as crustal heterogeneity may modify the application of such models even a few tens of kilometres from the rupture. No model has yet successfully fit all the GPS data from the Landers earthquake, even after consideration of possible postseismic deformation. These deviations are well constrained, and reflect the activity of some as yet unmodeled processes.

Postseismic Deformation

In addition to elastic coscismic effects, complex patterns characterize the transient viscous deformation observed after the earthquake. Earthquake-relatedpostscismic deformation must be determined before evaluating the discrepancy between observed displacements and displacements predicted by elastic half-space modeling. No near-fault postscismic slip was observed from creep meters and small scale trilateration nets at several locations adjacent to the surface rupture in the weeks following the Landers earthquake (Sylvester, 1993, written communication). In contrast, more widely distributed GPS observations suggest that significant relaxationoccurred in both the near- and far- field (Shen et al., 1992). The closest sites for which GPS results have been determined are within kilometres of the rupture rather than metres, however. The maximum transient deformation occurred tens of kilometres from the rupture, at Goldstone and Hector (near our site Troy). Thus, the apparent discrepancy between conventional and GPS geodesy may reflect real differences in behavior of the lithosphere with distance from the fault, the greatest viscous relaxation Occurnng some tens of kilometres away. Geologic offsets and preliminary near-field geodetic results arc consistent with seismic moment(Sieh et al., 1993). Farther from the fault, discrepancies may be related to ascismic deformation.

A significant amount of postseismic deformation occurred before the JPL August 1992 GPS survey. Thus, the Mojave displacement vectors include both a dominant coseismic and a lesser postseismic signal. The postseismic effect is probably greatest at Troy. The nearby site Hector underwent significant relaxation (Shen et al., 1992). Thus, we attribute an estimated 30 mm dislocation of Troy to postseismic deformation. Such relaxation at Troy accounts for ~60% of the model discrepancy and -30% of the total slip by August 1992. At Goldstone (located tens of kilometres from the fault), 30% of the total slip was postscismic (Bock et al., 1993). After the

1979 Homestead Valley earthquake, 10% of the relaxation within hundreds of metres to 1 km from the fault was also postseismic (Stein and Lisowski, 1983). So, while model discrepancies at Troy could result partly from transient deformation, this dots not account for the full discrepancy; some deviation from homogeneous elastic behavior is required.

No local data that constrain postseismic deformation are available for Siberia and Monday. Model discrepancies at these sites are in direction rather than magnitude, however, and are also probably attributable to real deviations from elastic half-space behavior, Elastic half-space modeling predicts displacements with reference to a fixed fault plane, and thus does not account for rotation of the fault itself and accompanying block rotations in an absolute reference frame. In contrast, GPS measures changes in location in an absolute reference frame. Nevertheless, relating direction discrepancies to a simple fault rotation is not yet possible.

Landers is perhaps the first earthquake for which observations are sufficiently dense, precise, and widespread to test elastic half-space models in detail on a regional scale. Absolute displacements indicate deviation from the model. Calculations of changes in static stress within the crust which use the elastic half-space model, however, appear to accurate] y predict patterns of seismic failure for the Landers earthquake from its precursors in Joshua Tree and Palm Springs (Harris and Simpson, 1992; Stein ct al., 1992). Furthermore, overall patterns of deformation from radar interferometry agree well with patterns of deformation predicted by elastic half-space models (Massonnet et al., 1993), although these patterns have not yet been calibrated with absolute displacements. Nevertheless, regional GPS data strongly imply that coseismic deformation during the Landers earthquake does not match the predictions of simple elastic half space modeling. Crustal heterogeneity or unmodeled mechanical behavior of the earth's crust played a discernible role.

Tectonic Implications and Future Seismicity

Large-magnitude historic earthquakes in eastern California and western Nevada are concentrated along a belt of faults that includes those of the Mojave Desert, and the Owens Valley and Dixie Valley faults (Wallace, 1984). This belt is segmented by the transverse sinistral Garlock fault. Most of these large earthquakes have occurred on faults that are thought to have recurrence intervals of thousands or even tens of thousands of years (Wallace, 1984). Segments of the aligned fault systems have ruptured with unusual frequency over the past 125 yr; failure of one fault loads adjacent faults along strike, indicating where large earthquakes might occur in the near future. On this basis, Wallace (1984) accurate] y speculated that the Mojave Desert faults were vulnerable, together with two other seismic gaps along the eastern California seismic belt. Similarl y, concentrated Landers aftershocks near Barstow may be precursors to a very large earthquake in the spatial gap that lies between the Landers rupture and the Owens Valley fault. The Goldstone - Fort Irwin and Coso areas are also at risk.

Minimum cumulative displacement of 28.1 to 40.0+ km (since ca. 10 Ma or later) is estimated from geologic criteria across faults of the Eastern California shear zone in the central anti eastern Mojave Desert (Dokka, 1983). Geometric constraints imposed by a palinspastic reconstruction suggest a higher value of 65 km (Dokka and Travis, 1990). For every 1 km of offset, about 300 Landers-type seismic events are implied for a fault strike length of approximately 70 km. If we accept the 65 km value for total offset and that modern slip rates for the Mojave Desert (6.7 mm/yr; Sauber et al., 1986) were typical throughout the history of these faults, such faulting must have occurred over -10 my, If we take the conservative geological estimate of total slip across the zone, 28.1 km (Dokka, 1983), the longevity of Mojave dextral faults is substantially decreased to 4.0 Ma. Of the Mojave dextral faults, onl y southwestern faults are thought to be current] y active (Sauber et al., 1986; Dokka and Travis, 1990). These faults account for ~7 km of total slip, and thus the transition to faulting in the western part of the Mojave Desert may have happened as recently as 1 Ma or later, if the total slip rate within the Mojave Desert has remained constant.

A total slip rate for the shear zone of 6.7 mm/yr (Sauber et al., 1986) and presumed coseismic slip of -3.5 m indicate a recurrence interval for events of the Landers size for the central and southern Mojave Desert is ~500 yr. This calculation excludes possible aseismic creep and known smaller earthquakes, though their contribution to displacement maybe relative] y small. The .

recurrence interval for individual faults or surface ruptures is proportionally increased as slip is shared among several active faults, and is probably on the order of thousands of years.

CONCLUSIONS

Absolute displacements of sites in JPL's Mojave GPS network between May 1991 and August 1992 occurred on the centimetre to decimetre level. Variations in displacement vectors are spatially related to the surface rupture, and thus are attributed to the Landers earthquake and its aftereffects. Whereas secular strain accumulation has occurred during the 13 month interval, it is negligible compared to seismic effects.

Estimates of secular strain and postseismic deformation for the five-week interval between the earthquake and our GPS campaign allow first order modeling of a residual coseismic field. Resulting coseismic displacements deviate from the predictions of an elastic half-space model. The effects of regional-scale heterogeneity y in crustal structure or other unmodeled processes are implied by these results. Continued measurements will yield new constraints on the role and magnitude of postseismic deformation.

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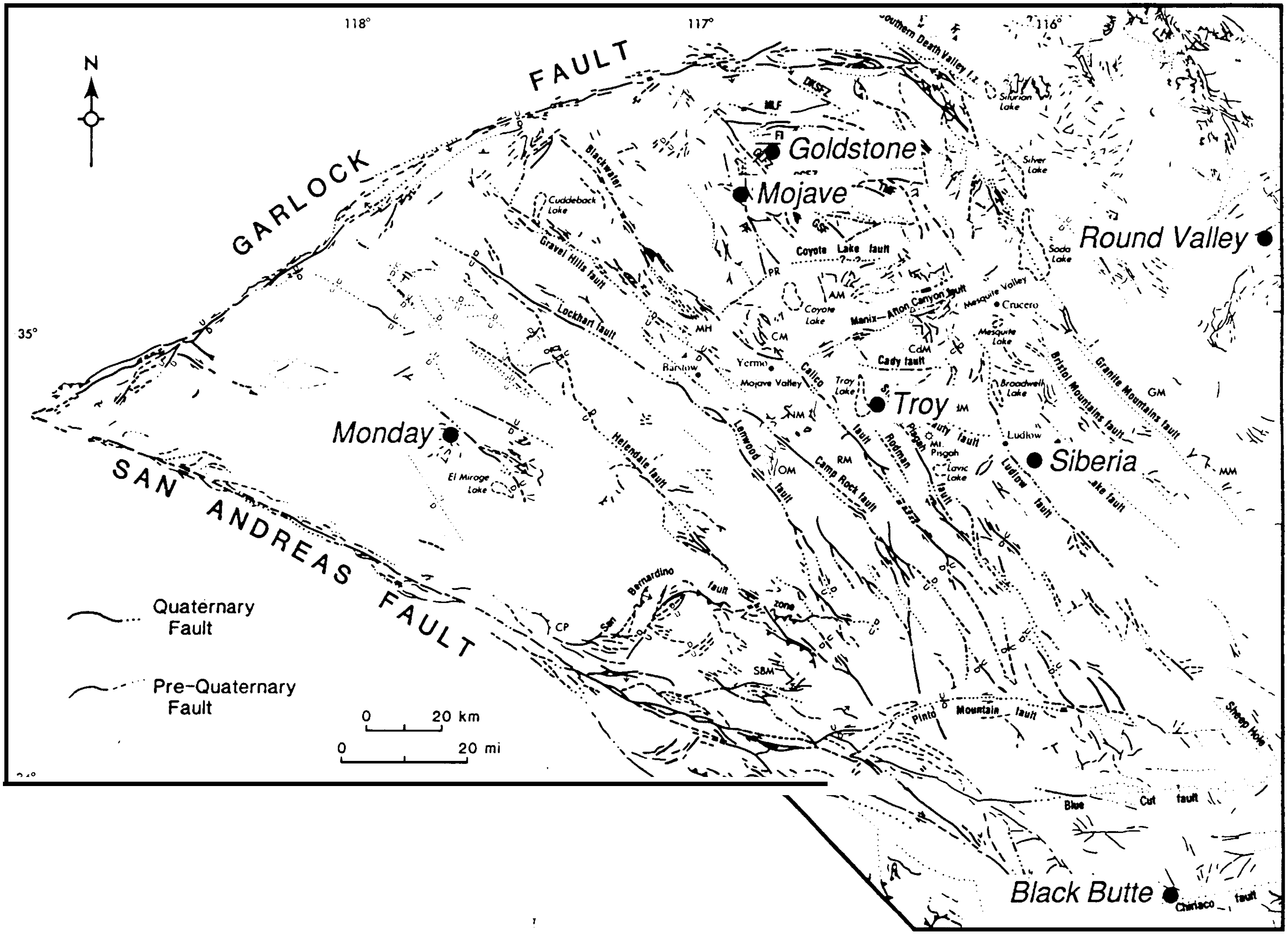
CAPTION

Figure 1. Faults of Eastern California shear zone within Mojave Desert and Mojave network GPS sites (large solid circles). Goldstone PGGA GPS site is also shown. Camp Rock and parallel dextral faults to the west now accommodate most, if not all, slip in Eastern California shear zone. This group includes the five faults that ruptured June 23, 1992. Six GPS sites were occupied in May 1991, and again in August 1992; these arc a subset of the more extensive JPL Mojave - Walker Lane network. Fault map from Dokka (1993).

Figure 2. Absolute displacements of Mojave network stations during the interval from May 19-23, 1991 to August 18-21, 1992. Coseismic displacements are shown for PGGA sites Goldstone, Pinyon Flat, and JPL, for the interval June 28 to June 29, 1992, as described by Blewitt et al. (1993). Thin lines are quaternary faults, heavy line is the Landers surface rupture. Large uncertainties in the east component result from relatively poor tracking network geometry for 1991 occupation and unresolved biases in both 1991 and 1992 experiments. Ellipses are 95% confidence regions. Some workers scale formal error by a factor of two to account for systemic effects that are not modeled (e. g., K L. Feigl and thirteen others, unpublished data). This scaling is not done here, as the magnitude of the 1991 reference frame errors is significant y larger than estimates of unmodeled errors. Dashed arrows are the model-predicted displacements (Mansinha and Smylie, 1971) for the Landers and Big Bear earthquakes based on the surface slip observations and aftershock distribution (see Blewitt et al., 1993, for parameters of model),



118°
117°
116°
35°
N
GARLOCK FAULT
SAN ANDREAS FAULT
Southern Death Valley f.z.
Goldstone
Mojave
Round Valley
Monday
Troy
Siberia
Black Butte
Silurian Lake
Silver Lake
Soda Lake
Cuddeback Lake
Blackwater
Gravel Hills fault
Lockhart fault
Coyote Lake fault
Coyote Lake
Manix–Afton Canyon fault
Mesquite Valley
Crucero
Mesquite Lake
Cady fault
Granite Mountains fault
Bristol Mountains fault
Broadwell Lake
Ludlow
Ludlow fault
Barstow
Yermo
Mojave Valley
Calico
Troy Lake
Helendale fault
Lenwood fault
Camp Rock fault
Rodman
Pisgah
Mt. Pisgah
Lavic Lake
El Mirage Lake
San Bernardino fault zone
Pinto Mountain fault
Blue Cut fault
Sheep Hole
Chiriaco fault
MLF
DKSFZ
FI
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AM
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NM
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MM
Quaternary Fault
Pre-Quaternary Fault
0 20 km
0 20 mi

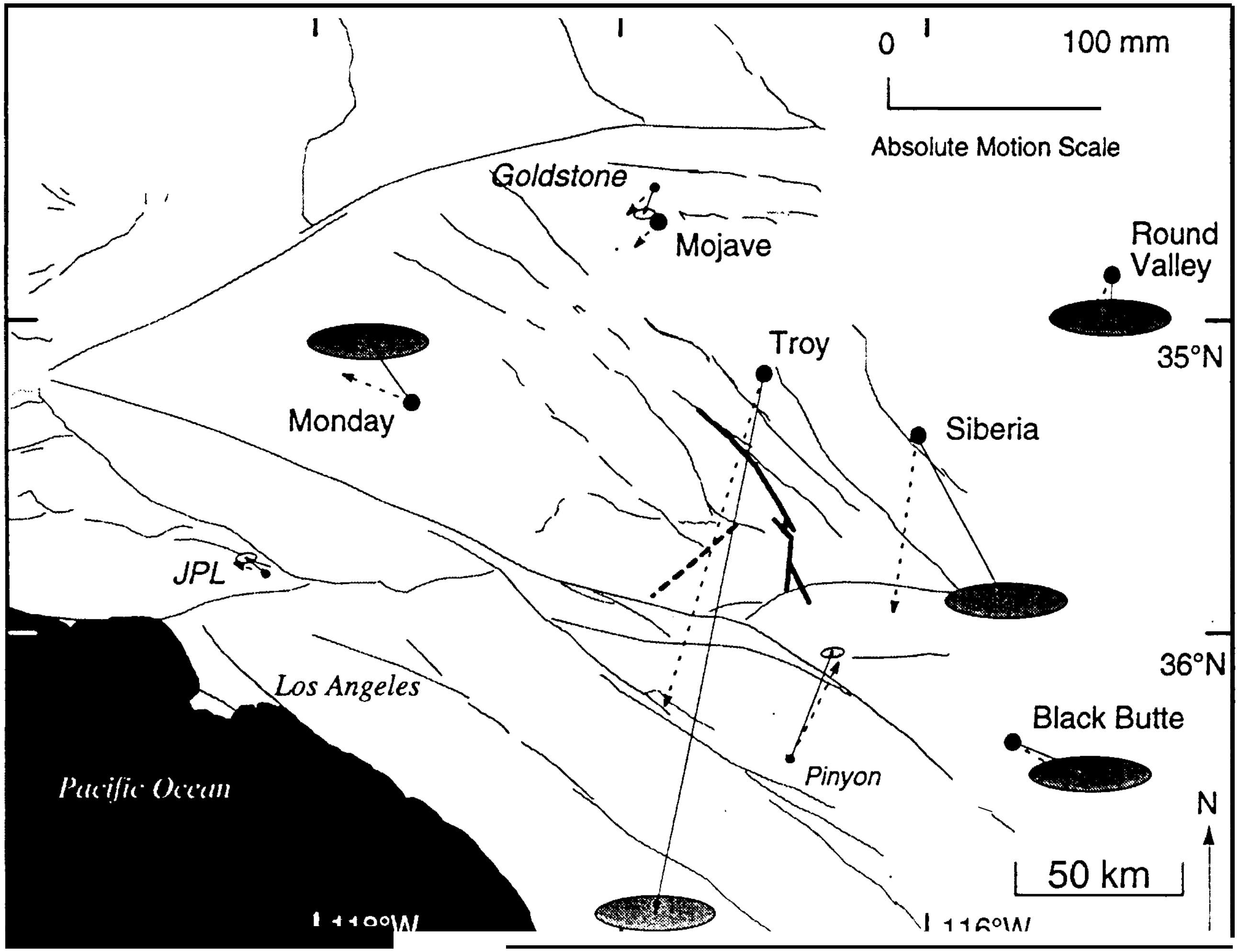
0
100 mm
Absolute Motion Scale
Goldstone
Mojave
Round
Valley
Troy
35°N
Monday
Siberia
JPL
36°N
Los Angeles
Black Butte
Pinyon
Pacific Ocean
N
50 km
116°W

TABLE 1. Absolute displacements of Mojave network sites.
May i991 -August 1992

Station	Displacements (m)*	
	North component	East component
Black Butte	-0.0040±0.0044	0.0429±0.0152
Monday	0.0407±0.0037	-0.01664.0128
Round Valley	-0.0075±0.0040	0.0043±0.0129
Siberia	-0.0644±0.0038	0.0464±0.0128
Troy	0.2336±0.0039	0.04644.0137
Mojave	-0,01 10±0.0010	-0.0050±0.0020

*In 1991, GPS observable data were collected with codeless Trimble 4000 SST receivers at all network stations for a minimum of five days per site. A mix of P-code Rogue and codeless Trimble receivers were used at global tracking sites. In 1992, GPS observable signals were collected by dual -frequency P-code Turbo Rogue GPS receivers for a minimum of four days at Mojave network sites, and Rogue receivers were used at global tracking sites.

Station positiona and carrier phase biases were estimated as real valued constants; station and satellite clocks were estimated as white-noise processes; and random-walk zenith tropospheric delays were estimated at each station. For the May 1991 solutions, global tracking stations were used as fiducial stations by fixing their coordinates to ITRF'91 values for May 1991 experiment, allowing the initial satellite state (position, velocity, and solar radiation pressure) to be estimated as constants For the August 1992 solutions, fiducial station coordinates were fixed for August 1992, and satellite orbits were fixed according to FLINN GPS orbit products (Zumberge et rd., 1992).

Uncertainties reflect 10 error.